

Simulating Ocean Fertilization: Effectiveness and Unintended Consequences

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Simulating Ocean Fertilization:
Effectiveness and Unintended Consequences

Ken Caldeira

Numerical simulation can throw some fresh light on the idea of ocean fertilization.

Analysis of the IS92A IPCC scenario shows that, by the end of this century, to stabilize climate at only a two-degree warming, even if climate sensitivity is at the end of the acceptable range, approximately 75 percent of all power production would need to come from carbon emission-free sources. If climate sensitivity is at the beginning of the accepted range, nearly all of our energy would need to come from carbon emission-free sources to hold global climate to a two-degree warming. We can perform the same sort of calculation for a range of climate sensitivities and a range of warmings. To achieve stabilization at 2°C for a mid-range climate sensitivity, we would have to add approximately one gigawatt of carbon-free primary power per day somewhere in the world.

The magnitude of this problem is enormous. There is not going to be a single solution. As other speakers have suggested, we need to work on diminishing energy demand, we need to work on sequestration and we need to develop non-fossil sources of energy.

Our speakers today have already discussed geologic storage and ocean storage by direct injection. Land biosphere storage has also been suggested, although it may be limited in its amounts and effectiveness, as well as limited by land availability. Some have proposed geo-chemical techniques, such as accelerating silicate or carbonate weathering.

One problem with putting CO₂ into the ocean is that nobody thinks putting CO₂ into the ocean is good for the ocean. We may want to do it if it turns out that the environmental consequences of putting carbon in the ocean are significantly less than the adverse consequences of putting it in the atmosphere. It only makes sense if the environmental consequences of releasing CO₂ into the environment are significantly worse than the consequences of putting it in the ocean.

As Peter Brewer pointed out, right now we're already putting two gigatons of carbon into the ocean each year. That works out to something like five kilograms per day per citizen. At present, we are putting carbon into the atmosphere, which may cause significant climate change. But eventually, the ocean will absorb about 80 percent of the carbon released to the atmosphere. The idea of ocean sequestration is to put carbon into the ocean deliberately and directly in an effort to avoid global warming. There is a potential of some adverse impacts on the marine environment, but we at least avoid most of the climate change.

I think the recognition that we're already sequestering carbon in the ocean is very important. The work that Peter Brewer and Jim Barry are doing on the effects of CO₂ on organisms in the ocean is some of the most important work being done today. If it turns out that that is an important concern, it is essential to continue to admit CO₂ to the atmosphere.

I want to talk mostly about simulations for ocean fertilization, focusing on different options. Other options have been proposed--for instance, adding chemicals to the ocean.

nitrate and phosphates to the oceans, as well as a set of inorganic strategies, the carbonate dissolution idea.

What is the basic idea behind ocean fertilization? As Peter Brewer pointed out, there is an exchange between the upper ocean and the deep ocean; the timing of the exchange is on the order of several centuries. The upper, mixed layer equilibrates with the atmosphere, roughly on a time scale of a year or so. The basic idea of iron fertilization is to add iron to the upper ocean, stimulating increased biological productivity, increased photosynthetic activity and generating more organic carbon--removing it from the surface. Some of this organic carbon then sinks into the deep ocean. The idea of fertilization is to remove carbon from the surface ocean, fix the CO_2 as organic matter and then sink it into the deep ocean. That is just a mostly gravitational sinking of particles. Because CO_2 has come from the surface ocean, the partial pressure of CO_2 in that surface ocean box has been decreased. That drives a compensating flux of CO_2 from the atmosphere into the ocean, drawing more CO_2 out of the atmosphere.

If this is as far as it would go, we'd have a permanent sequestration and that would be fine. But, time moves on. When this organic carbon gets into the deep ocean, it is oxidized back to CO_2 . This CO_2 can get mixed back up to the surface ocean and can out-gas back to the atmosphere; then it can actually gas back into the atmosphere, and so on. The CO_2 that went into the ocean over here sometimes out-gas back to the ocean. The ocean serves as a temporary storage system. I'll talk about the concept of temporary storage a little later.

A number of people have done idealized simulations using general circulation models and also schematic models on this question. Their simulations suggest that after fertilizing the southern ocean for a century, it would be possible to store carbon in a range of 100 gigatons to 250 gigatons. I worked on a highly idealized simulated fertilization with the premise that, working on everything south of 30 degrees, we could add micronutrients to the ocean to completely deplete the surface macronutrient phosphate. This was done using the Los Alamos POP model. One early discovery from this simulation was that, after only three years, some CO_2 had already begun to leak back into the atmosphere. If we compared 3 years, 30 years, and 300 years, that previously sequestered carbon was leaking back out over much of the southern ocean. By 300 years, there was significant leakage in the tropics. There are two reasons for that leakage. One is that carbon placed in the deep ocean eventually mixes back to the surface. Another reason is that, along with this organic carbon sent to the deep ocean, we also sent down nutrients, increasing the deep-ocean nutrient levels at the expense of the surface ocean. Biological productivity in other parts of the ocean began to diminish.

In this fertilization simulation, approximately 375 additional gigatons of carbon were stored in the ocean over a course of 400 years. On this time scale, the storage is on the order of about one gigaton per year. The net flux starts out close to eight gigatons per year. About a century in, there is about one gigaton. By 400 years, there is about one gigaton.

My sense is that these are upper boundary numbers. A real-life effort would have to fertilize the entire ocean south of 30 degrees. The areas that are fertilized probably not perform up to maximum possibilities. It is important to understand the limits of fertilization, insofar as it works and is environmentally and politically acceptable.

these things that might become part of the portfolio of responses. It is not itself to solve the problem.

Earlier I mentioned that as we continue fertilizing, we start moving phosphorus away from the upper ocean. Thus, the effectiveness of the iron fertilization over time as the surface ocean runs out of macronutrients. In addition, the carbon to the added exports from the surface ocean to the deep ocean decreases over time, because previously stored carbon is leaking back into the atmosphere.

What is the residence time of carbon in the ocean? The ocean likes to transport along surfaces of constant density. The density is controlled by temperature and salinity. At the surface, water outcrops at the colder Poles. There are surfaces in the deep ocean that are well ventilated. Even though more organic carbon is being transported, more is retained down there; whereas in other parts of the ocean, when CO₂ is deposited, the amount slips back into the atmosphere much more quickly.

We can ask how ocean carbon sequestration changes allowable emissions by calculating the net pros and cons as functions of a discount rate and a price trajectory. With a zero discount rate, there is no time preference, and no point doing ocean fertilization because you're not discounting future value. You should look at the discount rate minus the emission cost--because we could have a 10 percent discount rate but the cost of carbon emissions could rise at the same rate so that, once again, we gain nothing. Taking the range of discount rates that are typically in business, we would have to initially sequester three gigatons at \$33, in order to get one gigaton of carbon's worth of sequestration value. In other words, we take roughly a factor three for the fact that this is not a permanent sequestration.

In one simulation, organic carbon that sank into the deep ocean was oxidized, consuming ambient dissolved oxygen in the water column. I found that after 300 years, a layer had formed in the model ocean that had severe oxygen depletion--suggesting potential problems for oxygen-breathing organisms.

Green Sea Ventures estimates that the cost of iron fertilization would be \$100 per ton. But because it is a temporary sequestration, we must also consider that it is necessary to multiply the cost by an approximate factor of three to get the true value. Macronutrient strategies are considerably more expensive. There are suggestions that ships could just dribble along some iron to compensate for CO₂ admitted by ships.

A model is helpful for trying to understand the conceptual situation, but a much better one than the basic knowledge that went into it. There are many, many unknowns of this. We still don't know to what extent adding nutrients to the surface stimulates marine production of organic carbon and how that varies from environment to environment. Although, we're making progress in that area, we're not sure, if carbon production is increased, what fraction of that will sink to the deep ocean. Some organic carbon that sinks to the deep ocean, some carbon can mix up from below. Some CO₂ can come from the top. A deficit in the surface ocean may also be made up. Exactly how much a flux of CO₂ from the atmosphere will compensate for this flux is also unclear, as it is unclear how deep the CO₂ will sink in different environments before it is oxidized. Once it is oxidized, it is also unclear exactly how long it stays down there before it cycles back up to the surface. There are also some dis-

although I think I know the right answer, for how to properly account for gas seen in de-gassing situation.

If all the CO₂ that has been sequestered eventually leaks back into the atmosphere all we are really doing is just time-shifting emissions. We're putting it in, and it's leaking out 100 years from now, or 200 years from now. How can we say what the value of time-shifting an emission is? It's not simply economics. One reason for reducing emissions is to make time to invent new, carbon-emission-free energy technologies. Reducing emissions, in the short term, might be worth doing in anticipation of new technologies coming on line in the long term.

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